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ABSORPTION OF CENTIMETER AND DECIMETER WAVES BY THE MOLECULAR OXYGEN IN THE ATMOSPHERE

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S U M M A R Y

The results are described of an experimental investigation of radiowave absorption in the atmosphere in centimeter and decimeter bands. The values are derived for the absorption coefficients in these frequencies and the effective height of the absorbing atmosphere. Certain questions of theory are also reviewed.

* * *

The absorption of centimeter and decimeter radiowaves in the atmosphere takes place at the expense of absorption in molecular oxygen and it has a nonresonance character.

The theory of this phenomenon was given by Van Vleck [1]. Measurements of absorption in the atmosphere by radioastronomical methods in the centimeter band have shown a good agreement with the results forcast by theory, which subsequently served as a basis for the determination of the absorption coefficient by Van Vleck formulas in any wavelength [2]. However, research carried out in 1962 in the longwave part of the decimeter band in the 25 — 60 cm wavelength range [3] has shown a sharp departure between the experimental values and those computed by the Van Vleck theory.

This served as the basis for revising the theory, and it was ascertained as a result that the formal introduction by Van Vleck of nonresonance absorption is not justified and the **nonresonance** absorption mechanism cannot be of relaxational type. It was found to be possible to explain the

* POGLOSHCHENIYE RADIOVOLN SANTIMETROVOGO I DETSIMETROVOGO DIAPAZONOV MOLEKULYARNYM KISLORODOM V ATMOSFERE.

observed absorption with the aid of the spin-spin interaction of oxygen molecules at time of collisions [4]. Further calculations based upon the mechanism proposed are conducted in the present work.

In order to clarify the entire picture of absorption in decimeter and centimeter bands detailed measurements of absorption were conducted with the aid of a single method, of which the results are expounded below. It should be noted also that the conducting of radioastronomical measurements with the aid of a single method has become necessary in connection with the development of antenna calibration methods developed lately [5]; this led to the reconsideration of the heretofore available data, for example in [6].

When computing the absorption coefficient or the total absorption on the basis of data obtained by radioastronomical methods, the admitted value of the effective height of the absorbing atmosphere plays a substantial role. No experimental measurements of the effective absorption height were available to-date and its value was chosen on the basis of various theoretical reasons. This led to the assumption that the value of H_{eff} stood between 5 km [7] and 11 km [8], and it hampered the comparison of experimental data obtained by various authors.

This is why we shall begin the consideration of absorption by discussing the results of measurements of the effective height of the absorbing atmosphere.

The atmosphere radioemission temperature in a given direction is determined by a transfer equation; in case of plane-stratified atmosphere and plane earth its solution may be written in the form [6]

$$T(\varphi) = \int_0^\infty \varkappa(h)\, T(h)\, e^{-\int_0^{l(h)} \varkappa(h)\, dl}\, dl \quad (l = h \operatorname{cosec} \varphi), \qquad (1)$$

where φ is the angle of the site of observation direction; $\varkappa(h)$ is the absorption coefficient; $T(h)$ is the kinetic temperature of the atmosphere.

The form of the function $T(h)$ may be obtained by approximating the experimental data on temperature distribution in the atmosphere [9];

it may be admitted that we have to heights h = 15 km

$$T = T_0 - 6{,}5\,h \tag{2}$$

and in the 15 to 50 km range

$$T = T_0 - 97{,}5 + 2{,}4h. \tag{3}$$

In the following we shall consider the absorption in oxygen. The dependence of the absorption coefficient on height will be taken in the form

$$\varkappa = \varkappa_0 e^{-h/H}. \tag{4}$$

where H is the effective height. Inasmuch as the variation of absorption is determined by temperature and pressure, the value of the effective height will be different for heights below and above 15 km. We may assume for the estimates $H_1 = 4$ km and $H_2 = 2.3$ km, which will be justified below (19).

If $H\varkappa_0/\sin\varphi \ll 1$, which is always fulfilled at the above assumptions in the centimeter and decimeter bands, the integration of (1) is easily performed :

$$T_a(\varphi) = (T_0 - 6{,}5H)\frac{\varkappa_0 H}{\sin\varphi}\left(1 - 0{,}48\frac{\varkappa_0 H}{\sin\varphi}\right) - \\ -(T_0 - 97{,}5 - 6{,}5H)\frac{\varkappa_0 H}{\sin\varphi}\left(1 - \frac{\varkappa_0 H}{\sin\varphi}\right)e^{-15/H}. \tag{5}$$

Estimates show that the second term of the expression (5) constitutes at $H < 5$ km no more than 3 %, while the accounting of absorption above 15 km gives a correction of the order of 0.1 %.

It may be seen from the expression (5) that when measuring the absorption by radioastronomical methods it is possible to determine the absorption coefficient or the total absorption in the direction of the zenith $\varkappa_0 H$, provided the effective height is known. No direct measurements of H_{eff} were made to-date, so that when estimating the absorption, computed values of H_{eff} by the Van Vleck theory, utilizing the standard atmosphere model, were generally used in the national literature; then $H_{eff} = 5.3$ km [1].

For the true distributions of pressure and temperature similar calculations were conducted in [12]; this allowed to ascertain that $H_{eff} = 5 \pm 0.2$ km. in summertime and $H_{eff} = 3.9 \pm 0.4$ km in wintertime, thus undergoing strong seasonal variations, proportional to those of the temperature;

they may be approximated by the following expression :

$$H_{eff} = H_{eff}\,(1 - \beta T_o) \qquad (6)$$

Measuring the absorption at various heights above sea level, it is possible to determine the effective height experimentally.

According to (1), the temperature of atmosphere radioemission at the altitude h above the sea level is

$$T_a^h(\varphi) = (T_0 - 6{,}5h - 6{,}5H)\,\frac{\varkappa_0 H}{\sin\varphi}\left(1 - 0{,}48\,\frac{\varkappa_0 H}{\sin\varphi}\right)e^{-h/H} - \\ -(T_0 - 97{,}5 - 6{,}5H)\,\frac{\varkappa_0 H}{\sin\varphi}\left(1 - \frac{\varkappa_0 H}{\sin\varphi}\right)e^{-15/H}. \qquad (7)$$

At $H < 5$ km, $h \sim 3$ km, the second term in the expression (7) gives a correction of the order of 5%. Rejecting the second terms in (5) and (7), we find that when measuring at different altitudes, the value of the effective height can be found with a precision of the order of 5% with the aid of the following transcendental equation :

$$[T_a^h(90^\circ) \,/\, T_a(90^\circ)]\,e^{h/H} = [T_0 - 6{,}5\,H(T_0)] \,/\, [T_0 - 6{,}5h - 6{,}5H(T_0)]. \quad (8)$$

For the experimental determination of H_{eff}, measurements of the absorption were conducted in the wavelength $\lambda = 10$ cm for two heights by radioastronomical methods : at h = 3.2 km and at sea level.

At 3.2 km altitude and air temperature $T_h = 10^\circ$ C, the atmosphere radioemission temperature in the direction of the zenith is $T_a^h(90^\circ) = 1.5^\circ$ K and at sea level for air temperature $T_o = 20^\circ$ C, $T_a^o(90^\circ) = 3.5^\circ$K. Substituting these data in the equation (8) and taking into account the dependence of the effective height on temperature, we shall obtain, according to (6), the value of the effective temperature : $H_{eff} = 4$ km.

The values of total absorption in the direction of the zenith in 3.2 cm and in the 25 – 60 cm band, obtained as a result of temperature measurements of atmosphere's proper radioemission, were brought out in the works [3, 10, 11]. These values of total absorption must be subject to correction according to the experimental value of the effective height of absorption in oxygen, brought up above. The corrected results are compiled in Table 1.

In order to obtain a complete representation of radiowave absorption in the decimeter band, investigation of absorption was conducted in the 8, 9, 10, 11, 12, 13, 14, 15, 18.1, 21, 25.7 cm wavelengths. The measurements were conducted with a parabolic antenna of 4 m in diameter in nighttime and in clear weather. A band change-over radiometer, with a sensitivity of about 1° K at time constant of one second was used as a receiver. The antenna was calibrated by the radioemission of a hill situated in the antenna's Fraunhofer zone, which in these wavelengths constituting an absolutely absorbing body. The method of measurements was entirely analogous to that earlier applied in [3, 10].

At air temperature of 20°C the temperature of atmosphere radioemission in 8 — 25 cm was found to be equal to 3.5° K. The computed values of total absorption and of the absorption coefficient are compiled in Table 2, the precision in the determination of $\varkappa_0 H$ constituting $\pm 10\%$.

TABLE 1

λ, см	$\varkappa_0 H$ [3, 10, 11], дб	corrected values of $\varkappa_0 H$ db	$\varkappa_0$, дб/км
3,2	0,054 [10]	0,058	0,0145
25	0,058 * [3]	0,058	0,0145
31,2	0,06 [11]	0,063	0,0155
32,5	0,051 * [3]	0,051	0,0128
40,5	0,06 [11]	0,063	0,0155
44,3	0,052 [3]	0,056	0,0137
56,3	0,058 * [3]	0,058	0,0145
58,2	0,06 [11]	0,063	0,0155

TABLE 2

λ, см	$\varkappa_0 H$, дб	$\varkappa_0$, дб/км	λ, см	$\varkappa_0 H$, дб	$\varkappa_0$, дб/км
8	0,057	0,0142	14	0,057	0,0142
9	0,058	0,0145	15	0,054	0,0135
10	0,057	0,0142	18,1	0,058	0,0145
11	0,058	0,0145	21	0,055	0,0137
12	0,058	0,0145	25,7	0,054	0,0135
13	0,057	0,0142			

* The results obtained at reception of Sun's radioemission at various heights, which do not have to be reduced on account of the variation of H_{eff}, are marked by the asterisk.

It may be seen from Tables 1 and 2 that the total absorption in oxygen in the direction of the zenith $\varkappa_0$ H is distributed uniformly by the band from 3.2 cm to 60 cm and has the most probable value $\varkappa_0 H = 0.057$ db.

Inasmuch as the experimental values of $\varkappa_0$ H do not have peculiarities in the centimeter and decimeter waves, it may be reasonably assumed that the effective height too is constant along the band and equal to $H_{eff} = 4$ km. The theoretical considerations developed below also speak in favor of this last circumstance.

This allows to determine the absorption coefficient in oxygen on the basis of radioastronomical measurements and to find the shape of the absorption line in the band considered, which, as may be seen from Table 1 and Table 2, also offers a uniform distribution.

Let us now pause at some questions of theory.

A mechanism of nonresonance absorption of emission by molecular oxygen is proposed in [4], which is based upon the interaction of colliding paramagnetic molecules. At collisions of oxygen molecules with a spin $s = 1$, there arises a strong spin-spin interaction leading to shift and widening of the levels.

The solution of the problem is performed by the perturbation theory method. However, when considering the absorption in centimeter and decimeter bands, strong interactions have to be taken into account.

We shall also describe the colliding molecules by density two-part matrix (partitioned?) with initial conditions determined at time of collision t_o by the density matrix of the system situated in a thermodynamic equilibrium :

$$\rho(t_0) = ce^{-H(t_0)/kT}, \qquad c = spe^{-H(t_0)/kT}. \tag{9}$$

After collision the density matrix variation in time is described by the equation of motion in the matrix form :

$$i\hbar\rho_{mnm'n'} = \sum_{kl} [H_{mnkl}\rho_{klm'n'} - \rho_{mnkl}H_{klm'n'}]. \tag{10}$$

The total Hamiltonian of the system is [3]

$$H(t) = H_0^{(1)} + H_0^{(2)} + V^{(1)} \sin \omega t + V^{(2)} \sin \omega t + V^A + V^B, \tag{11}$$

where $H_o^{(i)}$ is the molecule's proper Hamiltonian; $V^{(i)} = -(\mu^{(i)}F)$ is the interaction energy of the dipole with the external field F ;

$$V^A = \frac{(\gamma\hbar)^2}{d_0^3} \frac{A}{\left(1 + \frac{v(t-t_0)}{d_0}\right)^3}; \tag{12}$$

$$V^B = \frac{(\gamma\hbar)^2}{d_0^3} \frac{B}{\left(1 + \frac{v(t-t_0)}{d_0}\right)^3}; \tag{13}$$

$$A = I_{z_j} I_{z_i} (1 - 3\cos^2\vartheta); \tag{14}$$

$$B = -\frac{1}{4}[(I_{x_j} + iI_{y_j})(I_{x_i} - iI_{y_i}) + (I_{x_i} + iI_{y_i})(I_{x_j} - iI_{y_j})](1 - 3\cos\vartheta). \tag{15}$$

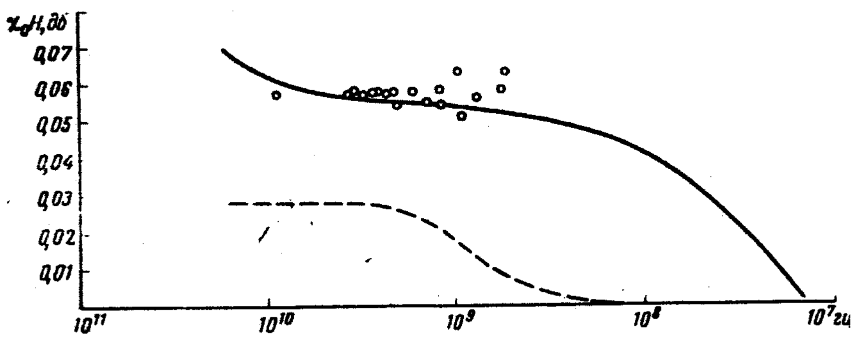
The following denotations are adopted in formulas (12) - (15) : d_o is the gas-kinetic crossection ; I_α is the projection of the spin I_i ; $\mu = \gamma\hbar I$ is the dipole magnetic moment ; ϑ is the angle between the axis z and r_{ij}

The terms V^A and V^B are responsible for the spin-spin relaxation in the dipole-dipole interaction.

The energy variation of one molecule during the time $t - t_0$ is

$$\Delta E = E_1(\rho_{1111} + \rho_{1212}) + E_2(\rho_{2222} + \rho_{2121}) - E_1(\overset{0}{\rho}_{1111} + \overset{0}{\rho}_{1212}) - E_2(\overset{0}{\rho}_{2222} + \overset{0}{\rho}_{2121}), \qquad (16)$$

where E_i are the proper numbers of the Hamiltonian $H_0^{(i)}$; $\rho_{mnm'n'}$ are the solutions of the equation (10).



If we assume that the last collision took place in the interval from $\underline{t - \theta}$ to $\underline{t - \theta - d\theta}$ with a probability $e^{-\theta/\tau}d\theta/\tau$, where τ is the mean time between two collisions, the mean molecule energy variation is

$$\overline{\Delta E} = \int_0^\infty \Delta E e^{-\theta/\tau} \frac{d\theta}{\tau}. \qquad (17)$$

The solution of the system (10) and the computation of the integral (17) were conducted with the help of a computer; the result of the calculation for $\tau = 10^{-9}$ sec is plotted in the figure, where the experimentally obtained points from Tables 1 and 2 are represented also. For comparison we figured there also the dashed curve characterizing the absorption computed by the Van Vleck theory ($\Delta\nu/c = 0.02\ cm^{-1}$).

It may be seen from the graph that the theory agrees satisfactorily with the experimental data.

For the calculation of the absorption coefficient in the region of high frequencies we may utilize the analytical expression brought out in [4], according to which the frequency dependence of the absorption is determined by the factor

../..

$$(\omega/\tau)\left[\frac{a}{\tau}\omega_{12}+|\omega_{12}-\omega|\right]\Big/[(\omega_{12}-\omega)^2+(1/\tau^2)] \qquad (18)$$

(ω_{12} is the frequency corresponding to the center of the absorption line) and the dependence on pressure and temperature has the form

$$p^3/T^{7/2}. \qquad (19)$$

Assuming for p and T a dependence on height characteristic for the standard atmosphere, i. e., $H_{eff} = 4$ km, if $h < 15$ km. As may be seen from the experiment's data, the value of the effective height also agrees well with the theory.

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*** THE END ***

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